Application of Digital Image Correlation for Monitoring Damage Progression in Composite Test Specimens

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Content of presentation

• Overview of Digital Image Correlation technique
• Examples of application
  – De-bond growth detection under CFRP repair laminates
  – Thick section laminates
• Conclusions
• Acknowledgements
Digital Image Correlation (DIC)

- technique used to map full-field 2D strain distributions and 3D deformations
- displacements and strains determined by correlating position of blocks of pixels
- requires a speckle pattern (grey intensity) providing sufficient surface detail
- NPL DIC kit: LAVision®

<table>
<thead>
<tr>
<th>Size of interrogation window</th>
<th>Accuracy of calculated vectors in pixels</th>
<th>Accuracy of calculated strain values</th>
</tr>
</thead>
<tbody>
<tr>
<td>128 x 128</td>
<td>0.01 to 0.03</td>
<td>0.094 %</td>
</tr>
<tr>
<td>64 x 64</td>
<td>0.02 to 0.05</td>
<td>0.3 %</td>
</tr>
<tr>
<td>32 x 32</td>
<td>0.05 to 0.2</td>
<td>1.25 %</td>
</tr>
<tr>
<td>16 x 16</td>
<td>0.1 to 0.3</td>
<td>5 %</td>
</tr>
</tbody>
</table>

(a) vector plot and (b) strain map calculated from a 16 x 16 interrogation window

(a) vector plot and (b) strain map calculated from a 128 x 128 interrogation window
Application 1
De-bond Growth Detection Under CFRP Repairs
**Composite over-wrap repairs**

- Composite over-wrap repairs used in the oil and gas industry

  - repair of corroded pipe-work and pipelines

  - applied to pipe systems that are leaking, i.e. a through pipe wall defect, usually caused by excessive internal corrosion.

- Repair materials

  - multi-axial fabrics: glass, carbon, aramid fibres

  - resins (matrix): epoxy, polyester, vinyl ester, polyurethane (good chemical resistance to hydrocarbons (e.g. alkanes, cyclo-alkanes)),

  - adhesives: epoxy, methacrylates, laminate resin systems

- Hand applied either using wet lay-up systems or prefabricated rolls of composite reinforcement bonded together on-site and allowed to cure
Objectives of application

Work undertaken within TSB Project ‘ACCLAIM’ (2006-2009) (NPL, ESR Technology, Doosan Babcock) – Case Study 5: Over-wrap repairs

• Steel plates with defined circular hole overlaid with carbon fibre composite repair
• Representative of pipe repairs
• Plates were aged in sea water and then pressure tested
• Project investigated the use of DIC to detect de-bond growth, stability of growth and measurement of out-of-plane deformation

Measurements as a function of applied pressure:

• 2D strain field on the surface of the repair laminate
  - track position of region of compressive strain in the vicinity of de-bond front
• derivation of 3D displacement vectors to yield Vz
  - comparison to analytical solution

\[
y(r) = P \left[ \frac{3(1-\nu^2)}{16Et^3} (a^2 - r^2)^2 + \frac{3}{8Gt} (a^2 - r^2) \right]
\]

Where:
- \( y \) = vertical displacement
- \( r \) = radial distance
- \( a \) = radius of de-bond area
- \( \nu \) = Poisson’s ratio
- \( E \) = Young’s modulus of the composite
- \( G \) = Shear modulus of the composite
Test specimens

- Test specimen details:
  - 300 mm square, 8 mm thick steel plate
  - central through hole was threaded ¼ inch BSP
  - effective hole diameter of 13 mm
  - central hole covered with 100 μm thick 25 mm diameter PTFE disk to avoid run through of the adhesive and to define an effective de-bond diameter
  - repair laminate - one layer of woven glass and four layers of hand laid quadraxial carbon fibre tow all impregnated with an ambient cure epoxy – effective thickness ~ 6 mm
Experimental set-up

Equipment
• LAVision DIC system
• Cameras: 2 x Imager Compact
  (1280 x 1024 pixel)
• 3D set-up
• Hand operated pump
• 2 pressure gauges – voltage out to DIC

Specimen Preparation
• AOI sprayed with white, grey and black paint

Field of View
• 150 x 150 mm,
• scaling ~ 130 µm/pixel

DIC Analysis
• Cross-correlation between 2 images
• Interrogation window:
  128 x 128 to 64 x 64 multi pass,
  50 and 75 % overlap
• Surface height calculation and subsequent 3D deformation analysis
Test procedure

- Samples pressurised to failure using hand-pump – no control over pressure ramp rate!

- Images recorded at 1 Hz throughout duration of test

- Pressure recorded as a function of image number

- Final failure observed at a pressure of 124 bar
Strain results – $E_{xx}$ 2D

$E_{xx}$

Image 30 - 20 bar
Image 35 - 33 bar
Image 40 - 55 bar
Image 45 - 61 bar

Image 50 - 98 bar
Image 55 - 120 bar
Image 58 - 124 bar
Image 64 - 18 bar
Strain results – $E_{yy}$ 2D

- Image 30 - 20 bar
- Image 35 - 33 bar
- Image 40 - 55 bar
- Image 45 - 61 bar
- Image 50 - 98 bar
- Image 55 - 120 bar
- Image 58 - 124 bar
- Image 64 - 18 bar
Strain results – 2D

Exx strain distribution – 28 bar

Exx strain profile along AA (28 bar)

Eyy for plate blow-off - DML plate 6

Eyy for plate blow-off - DML plate 6

Exx for plate blow-off - DML plate 6

Exx strain profile along AA (28 bar)
Strain gauge vs. DIC data

Comparison of Exx (%) from strain gauges and DIC at 14 mm radius

<table>
<thead>
<tr>
<th>Pressure (bar)</th>
<th>Strain gauge</th>
<th>DIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.26</td>
<td>0.22</td>
</tr>
<tr>
<td>33</td>
<td>0.51</td>
<td>0.43</td>
</tr>
<tr>
<td>62</td>
<td>1.1</td>
<td>0.94</td>
</tr>
</tbody>
</table>
3D results: 55 bar $V_z = 0.039$ mm (theoretical = 0.05 mm)
3D results: 61 bar $V_z = 0.042$ mm (theoretical = 0.06 mm)
3D results: 98 bar $V_z = 0.074$ mm (theoretical = 0.12 mm)
3D results: 120 bar $V_z = 0.076$ mm
3D results: 124 bar $V_z = 0.122$ mm
3D results: 50 bar $V_z = 0.514$ mm
3D results: 28 bar $V_z = 0.518$ mm
Conclusions

• DIC successfully applied to over-wrap plate blow-off tests

• Able to track approximate positions of compressive strain in the vicinity of the de-bond front – hence direction of growth

• Stable de-bond growth observed for only ~2-3 mm – then catastrophic propagation leading to failure

• DIC and strain gauge data in fair agreement

• Out-of-plane deformation measured using 3D DIC – approximate agreement with theoretical predictions – small displacements
Application 2
Damage monitoring in thick tensile coupons
Why test thick composites?

- Increasingly thick composite material sections are seeing use in a number of application areas e.g. marine, aerospace etc.
- Also seeing increased use in safety critical, primary structures
- Understanding and measurement of thick section behaviour is crucial
- For thick sections, focus has tended to be on the through-thickness properties
- Often neglected in-plane properties and the effect of physical size of test specimens on measured data
- Extensive development work undertaken on thin section test methods
- Very little for thick sections – no standards
- Approach has been to use thin section data for design or adapt thin section test methods for use with non-standard, large specimen geometries
- Key question – are data from thin section tests equivalent to thick section properties?
Thick tension specimen testing

• Standard tensile testing undertaken according to ISO 527-4
  – QI lay-up (+45°/0°/-45°/90°)_s
  – 250 x 25 x ~2.5 mm thick
  – Baseline ‘thin’ tensile properties
• Thick laminates for tensile testing:
  – (+45°/0°/-45°/90°)_8s – distributed – sub-laminate scaling
  – (+45°_8/0°_8/-45°_8/90°_8)_s – blocked – ply level scaling
• Nominal thickness of ~19-20 mm (cured ply thickness ~0.3 mm)
• Chose n=8 to provide a ‘worst’ case blocked lay-up to compare with distributed lay-up
Thick section coupon preparation - tension

- 3 coupons extracted from 300 x 600 mm panels
- Water jet cutting used to extract specimens
- Grit blasted and end-tabbed
- Post machining – splitting observed in specimens cut from blocked laminate…..
Ply splitting in thick, blocked laminate - +45° ply visible… also present in -45°, 90° and 0° ply blocks

Due to residual stress (formed during cure and cool down) acting on thick ply blocks and interlaminar stresses at free edges
Thick section coupons – tension testing

- 2 MN Dartec
- Specimens loaded to failure at 2 mm/min
- Load, crosshead displacement and strain (gauges and digital image correlation)
- Images recorded using 1 Megapixel camera – analysed using LAVision® system
Thick section coupons – tension DIC results

- DIC monitoring on edge of sample
- Damage progression for blocked laminate
- Strains plotted are maximum normal strains across cracks and delaminations
Thick section coupons – tension DIC results

(a) Formation of ply cracks in central 90° plies

(b) Damage progression consisting of extensive cracking of +45°, 90° and -45° plies plus delamination
## Thick section coupons – tension testing results

<table>
<thead>
<tr>
<th>Lay-up details</th>
<th>Nominal Thickness (mm)</th>
<th>Modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard (thin)</td>
<td>[+45°/0°/-45°/90°]_{s}</td>
<td>2.5</td>
<td>44.2 ± 0.6</td>
<td>551 ± 22</td>
</tr>
<tr>
<td>Distributed (thick)</td>
<td>[+45°/0°/-45°/90°]_{8s}</td>
<td>20</td>
<td>45.6 ± 0.5</td>
<td>540 ± 44</td>
</tr>
<tr>
<td>Blocked (thick)</td>
<td>[+45°/0°/-45°/90°]_{8s}</td>
<td>20</td>
<td>34.6 ± 5.7</td>
<td>392 ± 25</td>
</tr>
</tbody>
</table>

### Diagram

- **Sub-laminate**
- **Ply-level**
Conclusions

• DIC successfully used for monitoring the formation of damage on the edge of thick laminates
• Possible to see the opening of existing ply cracks in the 90° central ply block
• Significant knock down in tensile strength observed in blocked QI lay-up compared to thin and thick ‘distributed’ lay-ups
• If blocking plies then there is a requirement to characterise the tensile performance
Acknowledgements

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• Gurit Holdings AG for material supply

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